Coupled Neutronics-Thermalhydraulics LOCA Analysis

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Presented at Chulalongkorn University

Bangkok, Thailand, 1997 December

RFSP - Reactor Fuelling Simulation Program

The major finite-core computer program for design and analysis of CANDU reactors

- most detailed and realistic models
- recently added spatial-kinetics module, *CERBERUS, based on Improved Quasi-Static (IQS) Method

LOCA Analysis

Most important use of *CERBERUS is in study of power pulses following a Large Loss of Coolant

For this purpose, *CERBERUS is coupled to thermalhydraulics code, e.g. FIREBIRD

Lattice Properties

For a given fuel type (e.g., 37-element fuel), the quantity which has the largest influence on the lattice properties is the bundle fuel irradiation (burnup), which is bundle specific.

Therefore the lattice properties are different for every bundle.

Lattice Properties (Cont'd)

But other parameters also affect properties: coolant density, fuel temperature, absolute flux value, Xe-135 concentration, etc.

These parameters are not uniform in the core.

In *CERBERUS, history-based method used:

- effect of local parameters modelled
- also, history of local parameters taken into account

Lattice Properties (Cont'd)

History-based methodology:

- Individual lattice calculations for **each** fuel bundle at **each time** in the transient.
- Bundle-specific delayed-neutron fractions are also used.

LOCA Simulated

- At instantaneous snapshot in CANDU 6 operating history: FPD 2844
- 100% Pump-Suction Break
- Initial power = 103% FP
- 0.625 ppm boron in moderator
- Assumed terminated by SDS-1; break assumed in loop 2

Two-Tiered Scheme of Time Intervals

- solve the shape equation only at relatively large time steps (**macro intervals**),
- solve the point-kinetics-like equations for the amplitude and integrated precursor concentrations at small time steps (**micro intervals**).

Two-Tiered Scheme of Time Intervals

Times in transient, $t_1 = 0, t_2, t_3, \ldots$, at which we wish to calculate the shape function - Macro time intervals:

- at start of LOCA, before SDS, 50-100 ms;
- during SDS action, time for SORs to drop by one lattice pitch - ~10-50 ms;
- after SORs fully in, 1 s to several s.

Solution over Each Macro Interval

Coupling of all the equations forces the **iterative solution of the entire set** over each macro interval, until self-consistency is attained in each quantity: flux shape, amplitude, reactivity, precursor concentrations.

Each calculation [macro time step t_j] in transient is called a **"case"**, and the cases are numbered:

- Case 1: initial steady state at $t_1 = 0$.
- Case 2: steady-state adjoint, needed to calculate all subsequent core integrals.
- Cases 3, 4, 5, …: time-dependent cases at times t_2, t_3, t_4, etc.

Snapshot Model and History-Based Method

- Lattice code POWDERPUFS-V, incorporated in RFSP
- Empirical code for heavy-water-moderated lattices, based on research-reactor measurements
- Simple mathematical treatment, very quick

Snapshot Model and History-Based Method

- Lattice reactivity function of fuel irradiation
- Void reactivity also: ~ 15 milli-k for fresh fuel, ~10 milli-k for mid-burnup fuel
- Important to model the spatial distribution of fuel irradiation in core
- Bundle-specific delayed fractions computed

Neutronic-Thermohydraulic Coupling

- Detailed thermalhydraulics model: channels subdivided into "groups" according to pass, power, elevation
- 8 thermalhydraulics groups: 5 in critical pass of broken loop, 1 for other passes
- One axial node for each bundle in each group

Neutronic-Thermohydraulic Coupling

At each time macro time step:

- *CERBERUS sums up powers for channel groups, passes to FIREBIRD
- FIREBIRD calculates new coolant density, coolant temperature, fuel temperature for next step

Prevailing and Simulated Initial Conditions

For conservatism, many conditions prevailing at start of LOCA were changed in pessimistic direction, i.e. more severe accident

Prevailing and Simulated Initial Conditions

Boron in moderator:

- Actual: 0.4 ppm (~ 3 milli-k)
- Simulated: 0.625 ppm (~ 5 milli-k) - equivalent to about 12 days of "pre-fuelling" (overfuelling, in case of upcoming fuelling-machine maintenance)

Boron increases void reactivity

Prevailing and Simulated Initial Conditions

Reactor Power:

- Actual: 100% FP = 2061.4 MW
- Simulated: 103% FP = 2123.2 MW - to account for uncertainty in power measurement

Higher power: higher stored heat, higher fuel enthalpy

Prevailing and Simulated Initial Conditions

Coolant purity:

- Actual: 98.89 atom %
- Simulated: 94.26 atom %: minimum operational purity = 97.15 atom %, further artificially reduced to account for assumed uncertainty of 1.6 mk in void reactivity

Prevailing and Simulated Initial Conditions

Pressure-tube creep:

- Actual: FPD 2844 = 9 years at 90% capacity factor
- Simulated: 20 years at 90% capacity factor, ~3.5 % average increase in pressure-tube radius

SDS-1 Actuation

- Neutronic actuation assumed; process trips ignored
- Protective systems:
  - out-of-core ion chambers (trip on high rate of log power)
  - in-core ROP detectors (trip on high flux)

SDS-1 Actuation (cont'd)

- 2 logic channels tripped sufficient, but simulation requires all 3 logic channels to trip
- First trip signal is ignored; second (back-up) trip signal is used

SDS-1 Configuration

- CANDU 6 has 28 shutoff rods; simulation assumes only 26 rods operational (1 rod taken out for testing or maintenance, 1 rod fails to drop when actuated)
- Least effective set of 26 rods: SOR 01, 05 missing; "corner" of core not covered

Results

Note: some figures and tables show results for both instantaneous and "homogeneous" models.

"Homogeneous" results obtained with earlier, self-standing version of CERBERUS (**not** module of RFSP) with crude time-average model.

Results - Neutronic

- Time of actuation of SDS-1 = 0.495 s after break
- Note: break in loop 2 selected to maximize time of detection by SDS-1 ion chambers; loop-1 break would have been detected earlier
- Rods enter core, "bite" reactivity at 0.883 s

Results - Neutronic (Cont'd)

- Peak reactivity = 4.08 milli-k [far from prompt criticality of ~ 5.84 milli-k]
- Rods reach full insertion at ~ 2.1 s
- Reactivity levels off at -76 milli-k

Results - Neutronic (Cont'd)

- Bundle with highest deposited energy:

  P05-7

- Its peak power, relative to steady-state power = 3.65 at 1.229 s
- Total energy added to P05-7 = 3.557 MW·s
  = 4.298 initial-power-seconds

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Results - Neutronic (Cont'd)

- Apply P05-7 transient to hot pin of bundle at highest possible power (licensing limit) = 935 kW
- Hot pin of 37-element fuel is outer pin, power relative to average pin is 1.113

Results - Neutronic (Cont'd)

- Total fuel enthalpy (stored energy + energy deposited by power pulse) in hot pin of P05-7 = 589.6 J/g(U)
- Margin to conservative limit for fuel breakup (840 J/g(U)) = 250.4 J/g(U) [29.8%]

Summary

- Spatial-kinetics module of RFSP is *CERBERUS
- Based on IQS method
- Allows simulation of LOCAs with most detailed models
- Allows simulations in snapshot models of core

Summary

- For LOCA simulations, coupled neutronics-thermalhydraulics calculations are now the standard
- Typical LOCA safety analysis artificially changes many parameters in pessimistic direction for conservatism